

Electricity

The Quick Path to Carrying Nuclear Energy to the Transportation Sector

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Nuclear Hydrogen Invited Panel

“ . . . so that America can lead the world in developing clean, hydrogen-powered automobiles . . . first car driven by a child born today could be powered by hydrogen . . . to make our air significantly cleaner and our country much less dependent on foreign sources of energy.”

President George W. Bush
State of the Union Address
January 28, 2003

My talk today:

- Cleaner air and reduced energy dependence now
- Another view of applying stationary-source energy to transportation with a focus on our most-efficient, lowest-cost energy carrier — Electricity
- Plug-In Hybrid Electric Vehicles (PHEVs)
- Battery vs. fuel cell capital costs
- Nuclear electricity vs. nuclear hydrogen costs
- Questions
- Opinions
- References on final page

Hydrogen

- 9 Mt (40 GW_{H₂HHV}) of H₂ used in US/yr
- H₂ < 1.5% US energy base (which is > 3,000 GW)
- 95% of H₂ from Steam Methane Reformation (SMR)
- Natural Gas Floor Price ≈ \$5/MBtu (Note: Spot “Henry Hub” Price varies but not presently predicted to *permanently* exceed \$9/MBtu in next couple decades)
- SMR at \$9/MBtu ≡ Room-Temperature Electrolysis at 4¢/kWh
- Hydrogen after Natural Gas? The market goes to the provider of the lowest-cost, grid-distributed electricity.
- **If we keep nuclear energy available, viable and sustainable as the lowest-cost, 21st-Century electricity provider, then we have already captured the post-methane hydrogen production market.**



Nuclear Hydrogen Fuel Costs Three Times More Than Nuclear Electricity

Using **3-3.5 ¢/kWh** as a placeholder price (note: being associated with AP1000-Rankine and claimed by VHTGR-Brayton).

Electricity-Hydrogen-Electricity		Nuclear Electricity @ 3-3.5 ¢/kWh	
0.90	1000 km (230 kV, 500 A, 3Φ)	0.90	1000 km (230 kV, 500 A, 3Φ)
0.95	AC-DC	0.95	AC-DC
0.65	Room-Temp Electrolysis	0.80	Li-ion battery IN-OUT
0.87	Compress to 800 bar	0.95	DC-AC
0.50	Fuel Cell		
0.95	DC-AC		
$\eta = 23\%$		$\eta = 65\%$	
starting with 3-3.5 ¢/kWh grid electricity, the transportation consumer pays		4.6-5.4 ¢/kWh to auto's E motor	
12-14 ¢/kWh to auto's E motor			



High-Temperature Central Plant Nuclear Hydrogen Fuel Costs Two Times More Than Nuclear Electricity

Nuclear Central Plant Hydrogen High-Temp Electrolysis ($\eta = 0.45$) SH2 = 3.3-3.9 ¢/kWh-eq		Nuclear Electricity @ 3-3.5 ¢/kWh could be AP1000-Rankine ($\eta = 0.32$) could be VHTGR-Brayton ($\eta = 0.50$)	
0.90	1000km pipeline	0.90	1000 km (230 kV, 500 A, 3 Φ)
0.87	Compress to 800 bar	0.95	AC-DC
0.50	Fuel Cell	0.80	Li-ion battery IN-OUT
0.95	DC-AC	0.95	DC-AC
$\eta = 37\%$		$\eta = 65\%$	
starting with 3.3-3.9 ¢/kWh-eq central plant hydrogen or 3-3.5 ¢/kWh grid electricity, the transportation consumer pays 9-10.5 ¢/kWh to auto's E motor		4.6-5.4 ¢/kWh to auto's E motor	

Industrial Hydrogen User With A Co-Located Nuclear Plant

Nuclear Central Plant Hydrogen High-Temp Electrolysis ($\eta = 0.45$) SH2 = 3.3-3.9 ¢/kWh-eq		Nuclear Electricity @ 3-3.5 ¢/kWh could be AP1000-Rankine ($\eta = 0.32$) could be VHTGR-Brayton ($\eta = 0.50$)	
		0.65	Room-Temp Electrolysis
$\eta = 100\%$		$\eta = 65\%$	
starting with co-located 3.3-3.9 ¢/kWh-eq hydrogen or co-located 3-3.5 ¢/kWh electricity, the industrial hydrogen user pays \$ 1.3-1.5/kg H2		\$ 1.8-2.1/kg H2	

Co-located high-temperature electrolysis facility should save the industrial hydrogen user $\approx 28\%$ on their hydrogen feedstock costs compared to a co-located reactor supplying electricity for room-temperature electrolysis.

A Few Observations

"The committee believes that the transition to a hydrogen fuel system will best be accomplished initially through **distributed production** of hydrogen because distributed generation avoids many of the substantial infrastructure barriers faced by centralized generation . . . small hydrogen-production units located at dispensing stations can produce hydrogen through electrolysis . . . electricity transmission and distribution systems already exist; for distributed generation of hydrogen, these systems would need to be expanded only moderately in the early years of the transition."

National Research Council and National Academy of Engineering of the National Academies, 2004

- Nuclear electricity already captures the post-methane hydrogen production market if we keep nuclear energy available, viable and sustainable as the provider of the lowest-cost electricity.
- High-temperature central plant concept (neglecting infrastructure amortization) might trim $\approx 25\%$ off the nuclear hydrogen cost for a transportation consumer and it ought to trim $\approx 28\%$ off the nuclear hydrogen cost for an industrial user.
- **Nuclear hydrogen will always cost more than nuclear electricity.**
 - 3 times more by low-temperature distributed production
 - 2 times more by high-temperature central plant production



Auto Fuel Cell System Capital Cost is ≥ 10 Times More Expensive Than Auto Battery System Capital Cost

Comparing Batteries with Internal Combustion Engines (ICEs)

- Li-ion Batteries $\approx \$83/\text{MJ}$
- Cost needs to be $\approx \$28/\text{MJ}$ to be cost equivalent with ICE
- Battery systems are a factor of **3** more costly than ICEs

Comparing Fuel Cells with ICEs

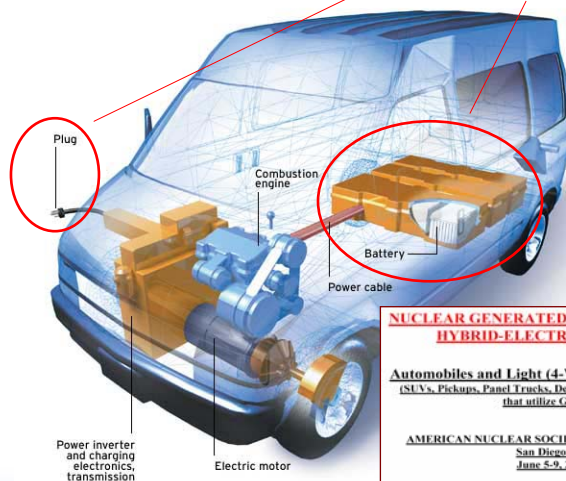
- Fuel Cells $\approx \$3000/\text{kW}$ to produce
- Cost needs to be $\approx \$35/\text{kW}$ to be cost equivalent with ICE
- Fuel Cell Systems are a factor of **85** more costly than ICEs

$$85/3 \approx 28 \geq 10$$



Plug-In Hybrid Electric Vehicles

PHEV = hybrid + **plug** + **larger battery**



NUCLEAR GENERATED ELECTRICITY FOR HYBRID-ELECTRIC VEHICLES

Automobiles and Light (4-Wheel) Truck Vehicles
(SUVs, Pickups, Panel Trucks, Delivery Vans, Minibuses, etc)
that utilize Gasoline

AMERICAN NUCLEAR SOCIETY ANNUAL MEETING
San Diego, CA
June 4-9, 2004

ROBERT E. UHRIG
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University of Tennessee, Knoxville



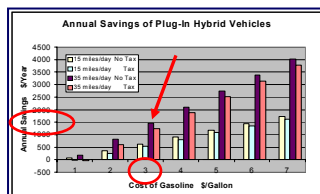
≈ 6-yr Payoff for an After-Market 35-mi E-Range “Plug-In” Modification

\$600/kWh (quote from VALENCE) * 0.27 kWh/mi = \$160 per mile of battery capacity

35 miles of E-range * \$160/mi = \$5600 in Li-ion batteries

Add \$2400 for AC-DC converter/charger and plug

Σ = \$8000 to add 35 mi of all-electric range to a Prius-sized Hybrid



≈ 90 bbl oil were NOT imported
≈ 35 tons of CO₂ were NOT emitted

Uhrig's Model: Save 70+% of 9E6 bbl oil/day!!!
≈ 250 GWe new nuclear needed!!!



More Observations

- The hydrogen energy delivery system is ≥ 10 times more expensive than the an equivalently capable energy delivery system based on Li-ion batteries.

“None of the existing technologies are a competitive choice for the consumer. The most promising hydrogen-engine technologies require factors of 10 to 100 improvements in cost or performance in order to be competitive. . . Major scientific breakthroughs are required for the Hydrogen Initiative to succeed.”

American Physical Society, 2004

- Plug-In Hybrid Electric Vehicles are very close; indisputably decades closer than hydrogen.
 - Break-even investment payoff
 - Reduce oil imports today
 - Cleaner air today
 - Grow nuclear energy today
- Urban-Light and High-Speed Rail

Questions

- How sure are we that hydrogen is our big opportunity for carrying our nuclear energy to the transportation sector?
- Until we have a better understanding of how energy carrier options will evolve, why not be content with capturing the hydrogen market simply by being the provider of the lowest-cost electricity?
- If the hydrogen market need is genuine, won't the industrial hydrogen users be capable of determining when is the correct time to invest their profits to develop the higher-temperature central plant technologies?

Opinions

- A thoughtful evaluation of opportunities for carrying our nuclear energy to the transportation sector is warranted.
 - Electricity is likely to capture routine daily mileage
 - Stretch petroleum resources and reduce demand for hydrogen in petroleum processing
 - Dampen the rate of petroleum price increases
 - Postpone petroleum-ICE losing a cost-competitiveness edge
 - Interesting evolution possibilities for the non-electric, extended-range side of the PHEV (some of those use more hydrogen, some possibilities use less hydrogen)
 - Expect capture of market share by electricity to be permanent. Once people have become accustomed to meeting their routine daily mileage with the lowest-cost energy carrier, why would they ever choose to change the electric side of the PHEV?
- Electricity opportunities abound for nuclear energy.
 - PHEVs (250 GWe), Coal (230 GWe), NG-E (80 GWe), H₂ (40 GW_{H₂HHV} ≈ 65 GWe)
- We should focus on our fundamental nuclear issues to ensure that nuclear energy will be available, viable and sustainable as the provider of the lowest-cost, grid-distributed electricity.
 - Domestic and international fuel cycle issues



Quibus hoc dicitur non simile sit cuiusque creditur ab istis quibus laboro.
(Opinions expressed here may not represent my employer's opinions)

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Back-Up Slide: H2 Losses

Stage	Details	% of HHV	Energy consumed
AC-DC conversion	–	5	Electricity
Electrolysis	–	35	Electricity
Compression	200 bar	8	Electricity
	800 bar	13	Electricity
Liquefaction	Small plants	50	Electricity
	Large plants	30	Electricity
Chemical hydrides	CaH ₂ , LiH, etc.	60	Electricity
Road transport	200 km, 200 bar	13	Diesel fuel
	200 km, liquid	3	Diesel fuel
Pipeline	2000 km	20	Hydrogen
On-site generation	100 bar	50	Electricity
Transfer	100 to 850 bar	5	Electricity
Re-conversion	Fuel cell, 50%	50	Hydrogen
DC-AC conversion	–	5	Electricity

Back-Up Slide: Hydricity

Start with 1 kWh of AC electricity

0.95 AC-DC conversion

0.65 Electrolysis forming H₂

0.87 Compression of H₂ to 800 bar

0.50 Fuel Cell conversion to DC electricity

0.95 DC-AC conversion

$\pi = 0.26$

End with 0.26 kWh of AC electricity

**AC Electricity-H₂-AC Electricity Loop
returns only 1/4th of the
original AC Electricity**